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Jan Hendrik Hellmich, Ines Groß-Weege, Robert H. Schmitt
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Seamless AI integration through Plug & Produce approach

Jan Hendrik Hellmich
Research Fellow
Production Quality
Fraunhofer Institute for Production Technology IPT

Ines Groß-Weege
Research Fellow
Adaptive Production Control
Fraunhofer Institute for Production Technology IPT

Prof. Dr.-Ing. Robert H. Schmitt
Member of the board of directors of Fraunhofer IPT
and holder of the chair for Production Metrology and Quality
Management at the WZL | RWTH Aachen University

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Introduction

Motivation

In recent years, artificial intelligence (AI) applications are emerging in the field of manufacturing industry enabled by the greater availability of data. The rise of Industry 4.0 technologies has driven significant advancements in the realm of AI, fostering a greater adoption of this innovative technology. As a result, manufacturing environments are becoming increasingly dynamic and connected envisaging higher agility, productivity, and sustainability. Solutions such as data-driven predictive analytics and assisted decision-making are thereby contributing to an improved product quality, increased performance and cost reductions [15], [16].

However, the industrial adoption of such solutions is characterized by a high degree of complexity. Various challenges are faced such as real-time processing needs, high security requirements, the integration of heterogenous devices as well as large data volumes to be handled. Numerous organizations are not adequately prepared to address these issues which impedes the integration of AI solutions in the industrial context [15]. In connection with this subject, the vision of "Plug & Produce" was addressed. It is defined as the "capability of a production system to automatically identify a new or modified component and to integrate it correctly into the running production process without manual efforts and changes within the design or implementation of the remaining production system" [17]. This means, machines and devices can be interconnected instantaneously without the need of a specific driver installation or change in setting configurations. New components can be added rapidly and seamlessly, thus increasing flexibility, efficiency and interoperability in the manufacturing environment [18], [19].

With regard to the integration of AI applications to the shop floor, this concept is usually not applied as current AI pipelines are nowadays often detached from the production environment. They mostly only receive manual data input (e.g. csv files) and conversely, do not automatically deliver the AI output to the physical system. That is why the question arises how it can be achieved to integrate AI applications seamlessly to the shop floor by using a Plug & Produce approach [17], [18].

For the connection between AI application and physical assets, an Industrial Internet of Things (IIoT) connectivity framework has to be established. It incorporates the communication beginning from the physical layer (e.g. Ethernet or WiFi) over the transport layer which includes different machine protocols to the distributed data interoperability and management layer [19].

However, the challenges can be summarized as follows:

- The lack of clarity regarding the specific technologies required to link AI applications and machines poses a challenge [20].
- The market offers a diverse array of technologies, each with distinct characteristics [21].
- Selecting the appropriate option tailored to individual needs demands considerable expertise and research, thereby complicating the decision-making process [22].
- In addition, a structured approach for this problem is often not defined due to the individual requirements and different implementation options [23].

The ICNAP study "Seamless AI Integration through Plug & Produce approach" aims to address these challenges. Three primary objectives have been identified which form the foundation of this guideline:

- A comprehensive overview of available technologies on the market will be created, enabling customers to quickly identify the most suitable option for their specific use case.
- Key criteria will be established to facilitate the selection of suitable technologies and accelerate the conceptual process.
- A structured procedure will be derived, which should guide companies on how to seamlessly integrate AI into their production environments.
- Overall, the guideline envisions to reduce the effort required for technology research, enabling customers to transition into the implementation phase with greater efficiency and speed.

Structure of the report

The study aims to address these gaps and challenges and provides a guideline for companies to realize a seamless AI integration to the physical asset.

After a comprehensive description of the initial situation and the general concept of the study in the following chapter 5.2, the next chapter 5.3 presents the technologies relevant for connecting and linking AI applications to the machines. This chapter forms the scientific basis for identifying evaluation criteria for selecting the right technologies for the respective use case.

This is followed by a comprehensive analysis of the technologies, such as interfaces, databases and IIoT platforms, which play an important role in the development and implementation of seamless AI integration.

Chapter 5.5 presents the developed procedure of the guideline, which is made up of the previously developed content. The core of the guideline is a questionnaire, which is intended to support the company in the selection of technologies. A demonstrator will illustrate the relevance and selection of technologies for practical implementation in chapter 5.6. Finally, the results are summarized and a brief outlook for further work is given.

General concept of the study

The overall goal of the study is to support the identification and selection phase of suitable technologies for realizing a seamless AI integration at the shopfloor. An attempt is being made to achieve this goal by developing a comprehensive guideline to support the selection process for the key technologies.

The overview shown in Figure 13 serves to clarify the selected technology types which were defined as relevant for AI integration at the shopfloor. The aim is to realize a suitable connection between physical machines and AI applications into the existing environment as easily as possible.

But for most of the companies, it is not yet clear which technologies are available on the market and which are best suited to their own use case. To close this gap, this guide dives deeper into the selected technologies and analyzes which technologies meet which criteria that are relevant to the integration process and depend on different use cases.

Furthermore, in most cases, there is already a machine that performs a specific production step and is equipped with specific data interfaces. On the one hand, commands can be transmitted to the machine. On the other hand, it is also possible to retrieve production data from the machine to generate information from the operation.

In order to send the data between the machine interface and the AI application, different technologies like databases, middleware, machine protocols or IIoT platforms can be used to transfer the data and information between the two parties.

A. A middleware system is often required to distribute the data further between the devices. This makes it possible, for example, for several AI applications to receive production data from one machine. Furthermore, predictions made by the AI application can be transmitted back to the machine with any degree of automation.

B. For saving important data, it makes sense to store it in form of a database that is connected to the middleware. This also allows the AI application to incorporate historical data into the prediction.

C. If an IIoT platform is already in use or is to be used, this software platform already includes some components such as databases, middleware or various interfaces for connecting the various machines and devices in the network. Integrated AI applications of the IIoT platform can also be used or an external application can be connected to the platform.

D. Furthermore, the selection of the correct machine protocol is crucial for the transfer of information. Factors such as data speed, information size or usability of the protocol can be decisive for the selection of the protocol and success of the complete use case.

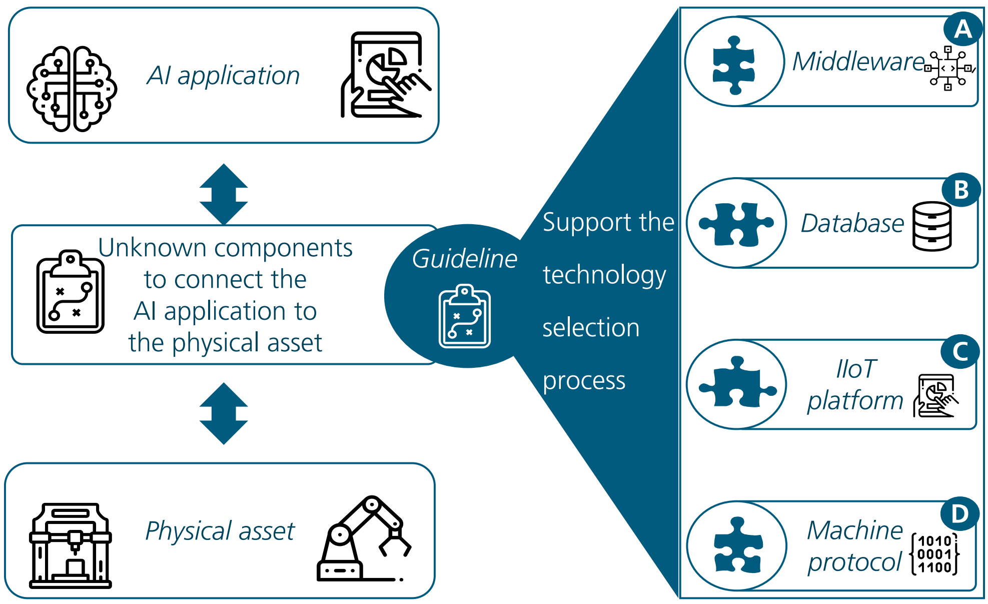

Figure 13: General concept of the study—Integration of AI application through Plug & Produce.

Theoretical background

In the scope of this study, several technologies in the context of IIoT will be presented and evaluated. This chapter aims at giving a brief overview about relevant technologies that need to be considered in the seamless AI integration process through Plug & Produce.

Furthermore, criteria have been elaborated that have an influence on the decision as to which AI integration strategy is best suited for the respective use cases. These criteria form the basis of this study on which the further procedure is built. Consequently, this chapter dives deeper into the selected criteria identified as crucial for the seamless AI integration process.

Relevant technologies along the seamless AI integration

After the completion of an extensive scientific research, core technologies along the seamless AI integration were identified in the field of industrial applications. These are middleware architectures, databases, IIoT platforms, communication protocols and AI applications. This section provides a short introduction on those core components building the connection between AI application and machines as depicted in the study's big picture.

Middleware

Middleware is a software layer that acts as an intermediary between different applications or components in a distributed system. It supports various protocols, such as HTTP, gRPC, or WebSocket, enabling seamless communication and data exchange. In the context of AI integration, middleware provides a standardized interface for deploying models, managing data flow, and orchestrating processes across multiple platforms. It ensures that AI components can interoperate efficiently with existing software infrastructures, regardless of underlying technology differences. This facilitates real-time data processing, model execution, and decision-making. By abstracting complex communication tasks, middleware enhances the scalability, reliability, and performance of AI-driven systems [24]–[26].

Databases

Databases are structured collections of data that are stored and accessed electronically. They are crucial for storing, managing, and retrieving large amounts of information efficiently.

A distinction is made between relational, NoSQL, object-oriented and hierarchical databases. While relational databases save data in a tabular format and are therefore only suited for structured data, NoSQL databases can also handle unstructured and semi-unstructured data. Subcategories of this type of databases are key-value, document and graph databases for example. In object-oriented databases, data is saved in form of objects containing both attributes and methods. Hierarchical databases organize data in a tree structure, where each child node has one parent node and parent nodes can have multiple child nodes [27]–[30].

IIoT platforms
Industrial Internet of Things (IIoT) platforms are specialized frameworks that facilitate the connection, management, and analysis of industrial devices and systems. These platforms enable the integration of various industrial protocols, data storage solutions, and analytics tools to optimize industrial operations [31].

Various tech companies offer their own IIoT platform such as Amazon, Microsoft or Siemens [32]–[34].

More than 620 IIoT platforms exist by now and the market is steadily growing [31].

Communication protocols
Machine protocols are standardized communication methods used to enable data exchange between different machines, devices, and systems. These protocols ensure that machines can interact seamlessly, even if they are from different manufacturers.

Examples for well-known protocols are MQTT, OPC UA, AMQP, CoAP and MTconnect. In the following these protocols are presented in more depth.

MQTT, which stands for Message Queuing Telemetry Transport, is a lightweight and reliable protocol designed for message transmission across networks in a one-to-many distribution model. Its efficiency makes MQTT one of the leading choices among publish/subscribe communication solutions [35], [36].

Open Platform Communication Unified Architecture (OPC UA) is designed to resolve the issue of interoperability among hardware devices by offering a standardized communication framework. Created by the OPC Foundation specifically for industrial automation, it aims to merge all existing protocols into a single, cohesive data model. It is also not just a protocol, but a meta modeling language, which serves the semantic modeling of information [37]–[39].

The Constrained Application Protocol (CoAP) is designed for communication between Internet of Things (IoT) devices that have limited resources. Thus, it is ideal for low-power devices or devices with small space of memory and narrowband networks with poor connection quality [35], [38].

Advanced Message Queuing Protocol (AMQP) is an open-standard protocol that allows for asynchronous communication by enabling messages to be stored in a queue. AMQP is designed to ensure security, reliability, and seamless interaction with other systems [35], [38].

MTConnect is an open, non-proprietary, and extensible standard that leverages XML to facilitate enhanced interoperability among machines. As a one-directional read-only protocol, MTConnect is typically employed for machine monitoring purposes [39], [40].

AI application
In production, AI applications such as predictive quality, predictive maintenance, quality control, and anomaly detection can offer significant benefits for companies. Predictive quality enables the forecasting of product quality through the analysis of historical data, allowing for early detection of potential quality issues. Predictive Maintenance aims to predict maintenance needs and possible machine failures, minimizing unplanned downtimes and enhancing efficiency. Quality control utilizes automated monitoring and analysis of production processes to ensure compliance with quality standards, thereby guaranteeing product consistency. Finally, anomaly detection helps to identify unusual patterns or deviations in production data, enabling quick resolution of potential problems [41].

Criteria to evaluate core technologies

In this study, 18 different criteria were defined that need to be kept in mind when integrating AI into the shop floor. They were selected after screening various research papers about the integration of IoT technologies in industrial environments and interviewing experts in the field. In order to focus on the decisive technologies, the various criteria are divided into different categories and will be matched to them individually. Furthermore, the complete criteria list is shown in Figure 14.

By looking from various perspectives, different criteria get into focus. From an AI perspective for example, it is crucial to ascertain whether the application must operate in real-time, or if the decision process should be automated or not. Meanwhile, from a machine perspective, it is essential to understand the available device resources. Conversely, the connection perspective offers insights into the significance of data security, for instance. These example criteria are supporting the selection process to find tailored technologies for the individual use case of a company and gives the developer a better sense of which properties of his solution he needs to pay attention to.

Furthermore, it is important to define each criterion once in order to create a uniform understanding. In the following a definition of one criterion is provided exemplarily for each of the three perspectives:

- **Real time capability:** The near-instantaneous processing of data and execution of actions so that systems can respond and adapt to changes and inputs as they occur.
- **Horizontal scalability:** The ability to manage an increasing number of devices.
- **Reliability:** A reliable protocol ensures the successful delivery of data to the intended recipients, where the data is received in full, without errors and in the correct order.

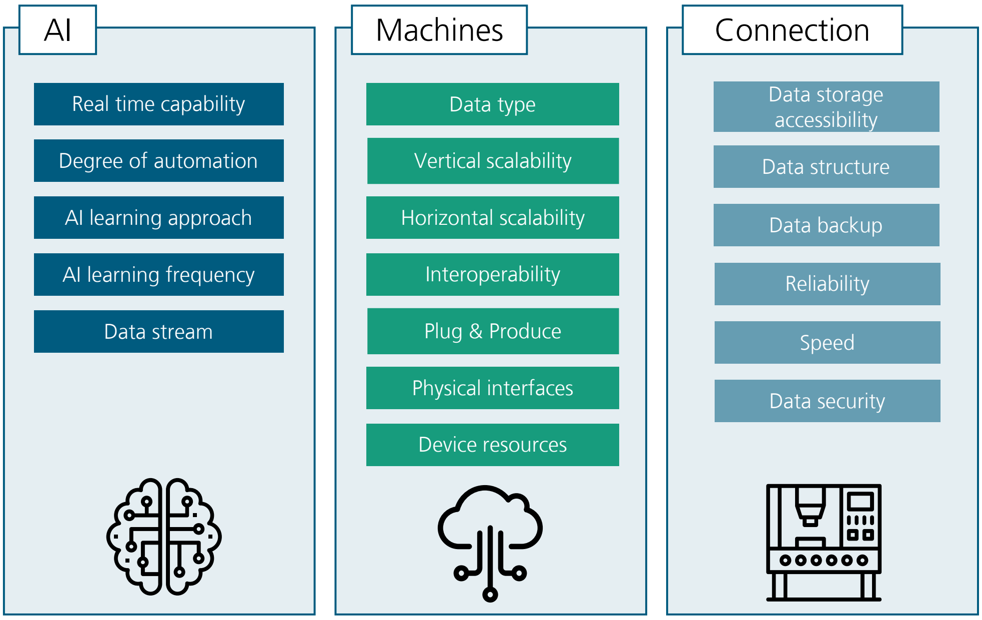

Figure 14: Selected criteria for technology evaluation.

Evaluation of selected technologies

In this chapter, the core technologies presented in section "theoretical background" are evaluated regarding the elaborated criteria introduced in its subsequent section. The aim here is to provide a comparable overview of individual technologies, which are evaluated on the basis of selected criteria. Hence, it builds the foundation on identifying which technologies offer the highest suitability for the connection components between machines and AI application, depending on the use case.

The evaluation of the core components was done by a comparison of the technologies' properties to the selected criteria using Harvey balls. These give an indication of the extent to which a criterion is fulfilled. The following applies: 0 % means the criterion is not fulfilled at all, 100 % that the criterion is very well or optimally fulfilled.

Machine protocols

In April 2024, an ICNAP workshop was conducted for the 24 member companies of the ICNAP community. The community was asked to specify which industrial technologies they are using in their production processes. Regarding machine protocols, the community stated, that they deployed MTconnect, MQTT and OPC UA among others.

After evaluating the results of the ICNAP workshop and screening various research articles regarding relevant communication protocols in the IIoT sector, five different machine protocols have been selected for further evaluation. These are MQTT, OPC UA, CoAP, AMQP and MTconnect.

The five machine protocols were evaluated regarding nine different criteria. These are data type, vertical and horizontal scalability, interoperability, device resources, reliability, speed and data security.

After having elaborated the protocol's properties regarding every single criterion, they were transferred in a graphical representation using the above-described Harvey balls. The results are shown in Figure 15.

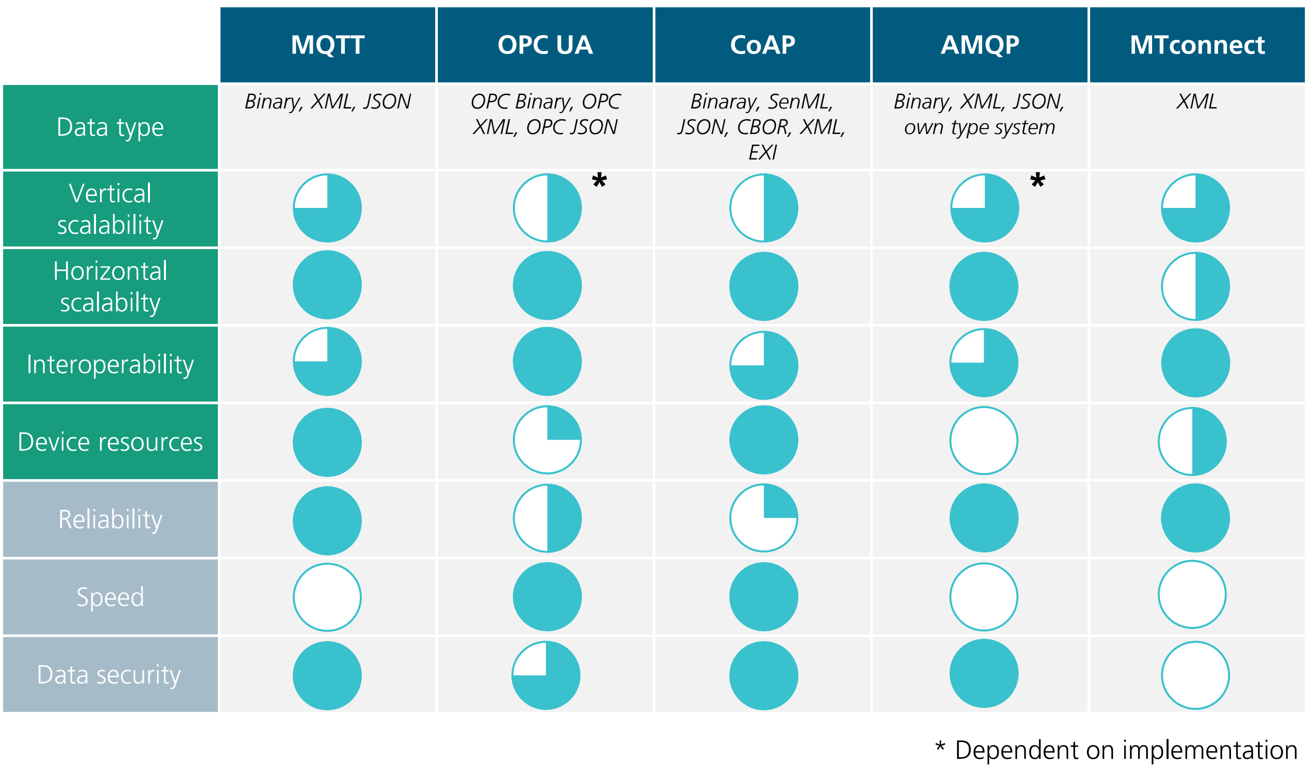

Figure 15: Evaluation between selected criteria and interfaces [38], [39], [42]–[45].

As can be seen, every evaluated protocol except MTconnect optimally fulfills the "Horizontal Scalability" criterion meaning that an increasing number of devices can be connected [42].

Regarding the criterion "Device Resources", the Harvey balls were filled if the protocol has low requirements on the device resources and left empty if high requirements are needed. Since MQTT and CoAP are especially suited for communication between devices with limited resources as low-power devices or narrowband networks with limited connection quality, they optimally fulfill the criterion [35], [43].

The reliability and speed criteria were thereby dependent on the underlying network communication protocols UDP and TCP. Those communication protocols relying on UDP as OPC UA and CoAP have their strengths in a fast data transfer rate. Whereas MQTT, AMQP and MTconnect do not focus on speed but on transferring every message reliably by guaranteeing message receipt, the correct message order and preventing duplication. These are features that are enabled by the TCP protocol [42], [44].

Databases

In the scope of this study four different categories of databases presented in section 5.3.1 were examined: Relational, NoSQL, object-oriented and hierarchical databases. Regarding the NoSQL database three subcategories were analyzed in more detail namely key-value, document and graph database. An overview about the chosen databases is given in Figure 16.

The chosen criteria for the evaluation were vertical and horizontal scalability, Plug & Produce, data structure, data backup and speed.

All databases fulfill the criterion "Vertical Scalability" effectively, handling high data volumes and complex scenarios. Relational, key-value, document, and graph databases are optimized for large-scale data, while object-oriented databases handle complex data models well. Hierarchical databases, while effective for hierarchical relationships, are less suited for large data volumes.

Most databases meet the criterion "Horizontal Scalability" by easily expanding through additional nodes or servers. Relational and hierarchical databases generally scale better vertically with fewer machines.

In terms of the criterion "Plug & Produce", integration ease varies. Relational and hierarchical databases, with their structured data and fixed schemas, require medium to complex integration efforts. Key-value and document databases offer easier integration due to their flexible schemas, whereas graph and object-oriented databases, with their complex data models, demand greater integration effort.

For the criterion "Data Structure", relational databases use structured, tabular formats. Key-value and document databases handle data in unstructured formats like key-value pairs and JSON documents. Graph databases utilize structures for complex relationships, while object-oriented and hierarchical databases use structured formats such as objects and tree structures.

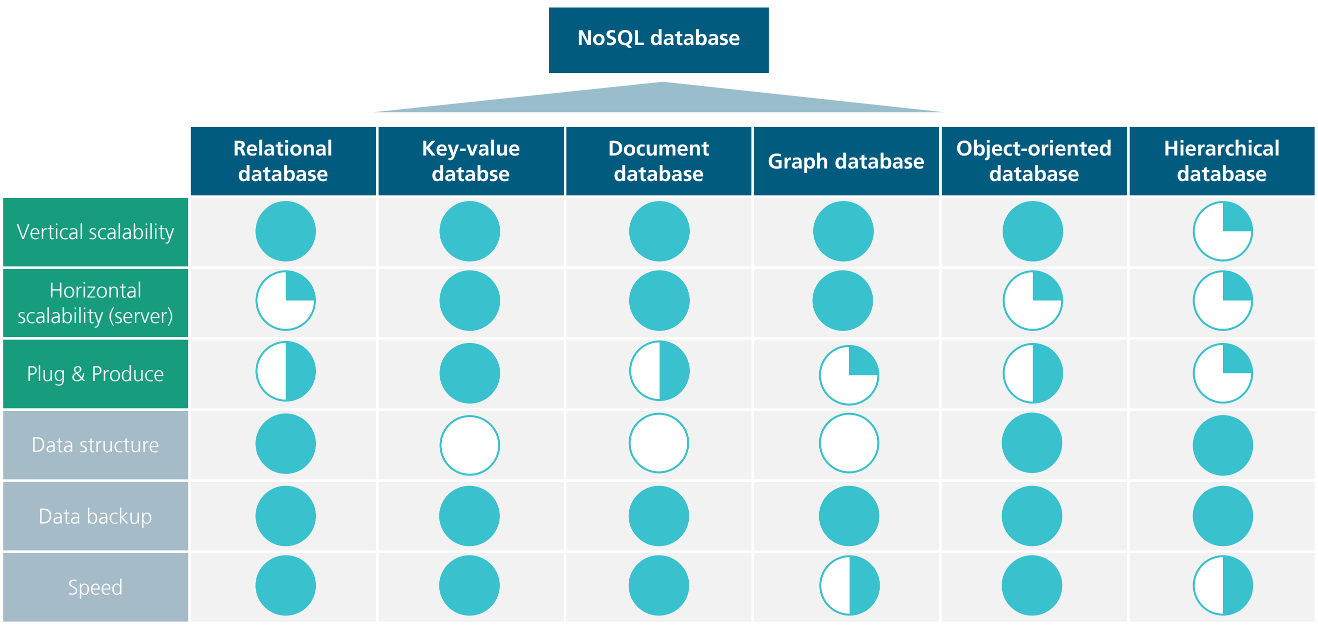

Figure 16: Evaluation between selected criteria and databases [46]–[52].

All databases fulfill the criterion "Data Backup" with well-established mechanisms for reliable data protection and recovery. Therefore, all Harvey balls are filled fully.

Regarding the criterion "Speed", most databases provide high performance with fast queries and transactions. Hierarchical and graph databases focus more on managing complex queries and data structures, with speed being a secondary concern

IIoT platforms

In this study, seven of the most widely recognized IIoT platforms were chosen and evaluated considering ten of the defined criteria. These platforms are Amazon AWS IoT, Bosch IoT Suite, GE Predix, IBM Watson IoT Suite, SAP Leonardo, Siemens Mindsphere and Microsoft Azure IoT Suite which were selected after extensive scientific research about the most known platforms in literature [53].

The ten chosen criteria are real-time, data stream, protocols, integrated AI application, openness/ external AI integration, vertical and horizontal scalability, interoperability, data security and data storage.

All of the evaluated IIoT platforms can perform in real-time or near real-time. They are all both vertically and horizontally scalable meaning that the data volume as well as the number of devices can be scaled according to the customer's needs. Since every IIoT platform reviewed is running on the cloud, the data storage criterion is optimally fulfilled too. Furthermore, data security methods are included in all the IIoT platforms evaluated [31], [53].

One difference between the platforms lies in the fact that not every platform allows integrating own AI applications. For example, Amazon AWS IoT and GE Predix support the unrestricted integration of customers' own applications while IBM Watson IoT Suite and SAP Leonardo do not. The number and type of supported machine protocols as well as the capability of interoperability also varies greatly [31], [53].

MQTT is supported by all of the evaluated platforms, OPC UA by most of them. CoAP is only usable within SAP Leonardo and Siemens Mindsphere [53], [54].

These points are crucial to consider in selecting the optimal IIoT platform.

There does not exist a single IIoT platform from the ones evaluated that satisfies all ten criteria. As with other IIoT technologies presented, it is therefore important to weigh up which criteria are particularly important, and which are less relevant for the own use case in order to arrive at a well-founded decision.

AI application

For the study different typical AI use cases were selected for the guideline. These are from the areas of predictive quality, predictive maintenance, quality control and anomaly detection. In addition to these use cases, there are others such as monitoring & diagnostics, layout optimization, ramp-up optimization and more, which are not considered in detail due to the scope of the study [41]. One typical example scenario for the selected use case was defined and will be descripted below. The example serves to illustrate the practical use of the guideline.

Selected use case: Visual, AI-based quality control for recognizing and adjusting the order of letters

In this use case, an AI application is utilized for image-based quality control. A camera captures images of various letters that need to be arranged in the correct order by individual movers. If the letters are not in the correct order, the AI communicates this information and sends the necessary adjustments to the machine. The movers then change the positions of the letters within seconds to match the new specified order. The AI application subsequently checks again to ensure that the correct formatting is in place. If the formatting is accurate, the use case concludes, allowing for the analysis of new letters to begin.

Based on the above-described example and the selected AI criteria the predictive quality use case was evaluated as presented in table 1.

	Use case: visual, AI-based quality control
Real time capability	yes
Degree of automation	Level 4
AI learning approach	Supervised learning
AI learning frequency	Discrete
Data stream	Continuous
Data type	Image data

Table 1: Evaluation of AI application: example predictive quality use case.

Development of a procedure including a questionnaire for identification of suitable technologies

A universal solution for the seamless integration of AI applications does not exist as it is highly dependent on the specific industrial use case. Therefore, it is essential to first identify the crucial aspects that must be considered during the integration process. Armed with these insights, a target-oriented decision in selecting the best suitable technologies along a smart factory can be made more easily thereby facilitating the discovery of the optimal AI integration pipeline.

For this purpose, four steps have been developed in this guideline, which are depicted in Figure 17. As initial situation, it is assumed that the machines to be connected to the AI application are known as well as the requirements for data transmission. The four steps start with the clarification of the specific use case by selecting the use case which should be considered for the AI integration process.

Taking the criteria presented in section "theoretical background" as a foundation, a question and answer catalog has been derived which aims at facilitating the identification of important criteria for the user. An extract is shown in Table 2 which should be filled out in the second step .

Using the resulting answers of the questionnaire, the technical realization follows in the last two steps. It begins with selecting the IIoT technologies presented in chapter "evaluation of selected technologies" for the AI integration pipeline by reviewing which of them are fulfilling the as important identified criteria. Conclusions can be drawn from this as to which databases, machine protocols and IIoT platforms are best suited for the use case. The last step consists of the actual implementation of the connection.

The procedure for the implementation starts with configuring the machine protocol via communication parameters as the IP address and the port. After that, data points must be defined (e.g. sensors, actuators) that are to be monitored and transmitted.

Once this has been done, there remain two options to choose from. The option to connect the developed AI application via a database to the shop floor. Or the option to use an IIoT platform and benefit from the additional feature of deploying already integrated AI tools. Since all IIoT platforms already incorporate data storage capabilities, an additional database is not needed.

For the first option ("Connection via database") the connection between the chosen database and the machines has to be set up via the selected machine protocol. Afterwards the AI application has to be connected to the database.

The second option ("Use of IIoT platform") includes registering all machines on the IIoT platform as devices. In the following the data transmission from the machines to the IIoT platform has to be configured via the chosen machine protocol. After that the AI application can be connected to the platform or the integrated solution can be used.

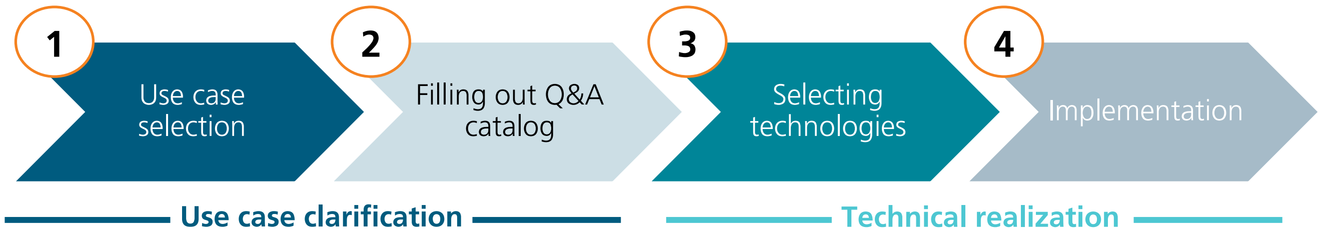

Figure 17: Guideline procedure.

Criteria	No.	Questions and Answers
Data Type	Q1	In what data type do your machines output their data?
	A1	Binary · Text files · Images · Audio/Video
Vertical Scalability	Q2	Is it important that a high data volume can be transferred per time (e.g. several megabytes per second)?
	A2	Yes · No
Horizontal Scalability	Q3	Is it important that an increasing number of devices can be connected (e.g. thousands of devices)?
	A3	Yes · No

Table 2: Extract from the created question & answer catalog.

Use case development

To validate the guideline the presented use case from chapter AI application was selected.

The use case includes a machine moving products to specific places and involving an integrated camera system. The complete information and communication flow of the selected use case is shown in Figure 18. The products are automatically moved to the camera of a tablet which takes pictures of them (A). The tablet incorporates the AI application which after screening the images, publishes its predictions to a broker (B-D). The machine represents the subscriber in this case and receives the predictions via the broker (D-F). Dependent on the obtained data, the machine's products are moved to a specific location managed by a control algorithm (F).

For this use case the guideline was used to choose the most suitable technologies. After the selection of the use case which represents step 1, in the next step of the guideline the question and answer catalog was filled out. Thus, the criteria reliability, interoperability and device resources were identified

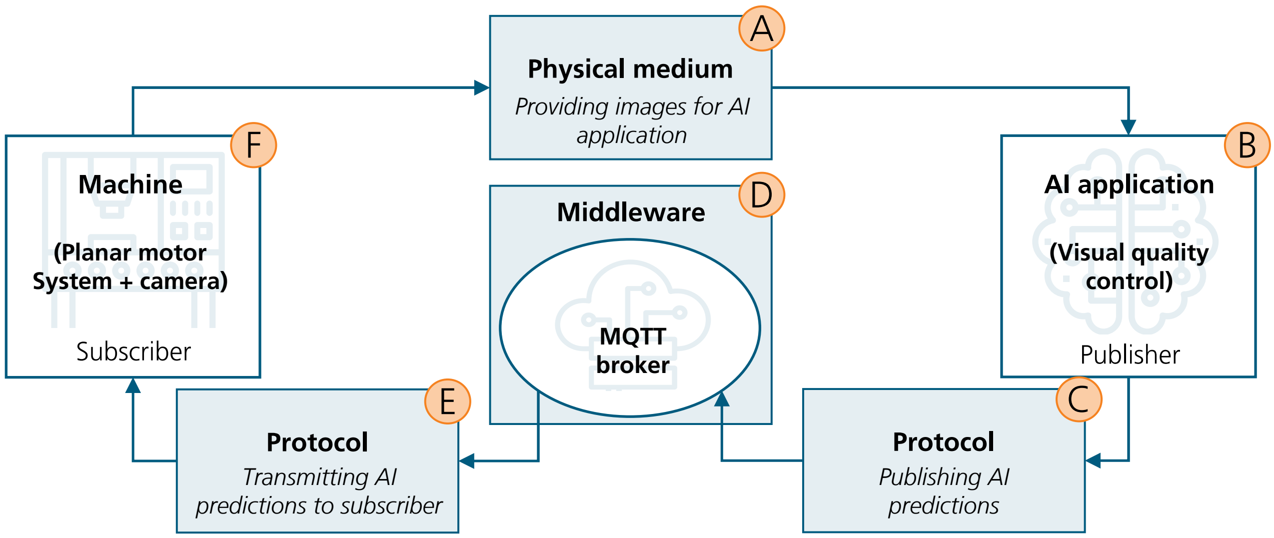

Figure 18: Demonstrator—Information and communication flow.

as crucial. A reliable transmission for example is needed, because otherwise, the control algorithm cannot accurately assign products to their designated positions. A high-speed communication is therefore not required as it is not a time-critical process but can also react after a few seconds and the machine can wait for the control algorithm's commands.

As the third step the guideline proposed MQTT as machine protocol which then was chosen for this use case.

Moreover, an MQTT broker was selected based on the selected protocol and the simplicity of connection.

An additional database is not needed because the storing of the detected data and information is not necessary for the use case. Finally, it should be mentioned that the machine is digitally connected to the internal internet, but no IIoT platform is required due to the small number of connected devices and their low complexity.

Finally in step 4 the implementation of the connection of the AI Application to the middleware and to the machine was developed.

Conclusion and outlook

In this study, a comprehensive overview of available technologies which are relevant for the AI to shopfloor integration. Based on that key criteria were defined to support the selection process of technologies.

Moreover, a guideline for supporting the process of a seamless integration of AI applications to the shop floor was developed. The guideline includes an extensive description on important technologies which are involved in this process.

By using the results of the study companies can shorten their worktime in research and identifying the right technology. Furthermore, through the developed questionnaire companies can create more suitable solutions, based on the answered questionnaire which is aligned with the starting situation of each individual company. Additional to that the guideline also brings all relevant stakeholder together, which promotes communication and implementation of the AI application on the shopfloor.

As outlined above, the developed guideline comprised four steps, starting with the selection of a use case into which an AI application is to be seamlessly integrated and the completion of a question-and-answer catalog. These two steps helped to identify important criteria for the respective use case and laid the foundation for finding the optimal AI integration strategy tailored to this use case in the following steps. Subsequently, suitable IIoT technologies could be selected by analyzing the provided evaluation tables and selecting the technologies that met the relevant criteria identified above. In this study, the focus was placed on machine protocols, databases and IIoT platforms as IIoT technologies. In addition, a use case was implemented in which an AI application was integrated into a production process and this guide was used to find the most suitable machine protocol.

As an outlook, the question-and-answer catalog could be expanded to include insights into which AI applications are best suited for certain machines and production scenarios. This expansion would empower users to identify the most appropriate AI tools to further refine and optimize their production processes.

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